

Exchange shift of stripe domains in antiferromagnetically coupled multilayers

N. S. Kiselev,* I. E. Dragunov, U.K. Rößler,† and A.N. Bogdanov
 IFW Dresden, Postfach 270116, D-01171 Dresden, Germany and
 Donetsk Institute for Physics and Technology, 83114 Donetsk, Ukraine
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Antiferromagnetically coupled multilayers with perpendicular anisotropy, as [CoPt]/Ru, Co/Ir, Fe/Au, display ferromagnetic stripe phases as the ground states. It is theoretically shown that the antiferromagnetic interlayer exchange causes a relative shift of domains in adjacent layers. This “exchange shift” is responsible for several recently observed effects: an anomalous broadening of domain walls, the formation of so-called “tiger-tail” patterns, and a “mixed state” of antiferromagnetic and ferromagnetic domains in [CoPt]/Ru multilayers. The derived analytical relations between the values of the shift and the strength of antiferromagnetic coupling provide an effective method for a quantitative determination of the interlayer exchange interactions.

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Nanoscale superlattices of antiferromagnetically coupled ferromagnetic layers have already become components of magnetoresistive devices. They are considered as promising materials for the emerging spin electronics and high-density storage technologies [1]. An interesting group of these *artificial* antiferromagnets belongs to systems with high perpendicular anisotropy (e. g. Co/Ru, Co/Ir, [Co/Pt]Ru, [Co/Pt]NiO superlattices) [2, 3, 4, 5]. Due to the strong competition between antiferromagnetic interlayer exchange and magnetostatic couplings [3, 6], nanoscale superlattices with strong perpendicular anisotropy display specific multidomain states and unusual magnetization processes [2, 3, 5, 7], which have no counterpart in other layered systems with perpendicular magnetization [8].

So far, theoretical analysis of magnetization states and processes in antiferromagnetically coupled multilayers with out-of-plane magnetization has been based on micromagnetic models of stripe domains, where the domain walls throughout the whole stack of the ferromagnetic layers sit exactly on top of each other [3, 6]. In our letter we show that this assumption is wrong. The antiferromagnetic interlayer coupling causes a lateral shift of the domain walls in the adjacent ferromagnetic layers. We develop a phenomenological theory of these complex stripe states. The analytical evaluation of a basic two-layer model shows that the formation and evolution of such “shifted” multidomain phases should appreciably influence the appearance and the magnetization processes of stripe states in perpendicular, antiferromagnetically coupled multilayers.

As a model we consider stripe domains in a superlattice composed of N identical layers of thickness h antiferromagnetically coupled via a spacer of thickness s . The stripe domain phase consists of domains with alternate magnetization \mathbf{M} along the z -axis perpendicular to the multilayer plane. The domains are separated by thin domain walls with a finite area energy density σ . The magnetic energy density of the model (Fig. 1 (a)) can

be written as a function of the stripe period D and the shift a

$$W = \frac{2\sigma N}{D} + 2\pi M^2 N w_m \pm \frac{J}{h} \left(1 - \frac{4a}{D}\right) (1 - N). \quad (1)$$

The first term in (1) describes the domain wall energy, w_m is the stray field energy, $J > 0$ is the antiferromagnetic exchange interaction. The upper (lower) sign corresponds to an (anti)parallel arrangement of the magnetization in the adjacent layers. We call these modes *ferro* and *antiferro* stripe phases.

We introduce a set of reduced geometrical parameters

$$p = 2\pi h/D, \quad u = 2a/D, \quad \nu = s/h \quad (2)$$

and two characteristic lengths

$$l = \sigma/(4\pi M^2), \quad \delta = J/(2\pi M^2) \quad (3)$$

describing the relative energy contributions of the domain walls (l) and the interlayer coupling (δ) in comparison to the stray field energy. Then, the reduced energy $w = W/(2\pi M^2 N)$ can be written

$$w(p, u) = 4p \frac{l}{h} + \frac{\delta}{h} \left(1 - \frac{1}{N}\right) (1 - 2u) + w_m(p, u). \quad (4)$$

The stray field energy $w_m(p, u)$ is derived by solving the corresponding magnetostatic problem

$$w_m = \frac{8}{\pi^2 p} \sum_{\text{odd } n}^{\infty} \frac{1}{n^3} \left[(1 - e^{-np}) - \sum_{k=1}^{N-1} f_k^{(n)}(p, u_k) \right], \quad (5)$$

where $f_k^{(n)}(p, u_k) = 2 \cos(\pi n u_k) \sinh^2(np/2) \exp(-\tau np)$, $u_k = u[1 - (-1)^k]/2$, and $\tau = 1 + \nu$.

The identity $\int_0^\infty t^{(m-1)} \exp(-nt) dt = (m-1)!/n^m$ allows one to transform the infinite sums in Eq. (5) into integrals on the interval $[0, 1]$ (for details, see similar cal-

culations in [6, 9])

$$w_m = 1 + \frac{4p}{\pi^2} \int_0^1 (1-t) \ln \left[\tanh \left(\frac{pt}{2} \right) \right] dt + \sum_{k=1}^{N-1} \left(1 - \frac{k}{N} \right) \Xi_k(p, u_k), \quad (6)$$

where $\Xi_k(p, u_k) = 2\Omega(p, u_k, \tau k) - \Omega(p, u_k, \tau k + 1) - \Omega_{\nu+1}(p, u_k, \tau k - 1)$, and

$$\Omega(p, u_k, \omega) = 4 \left(\frac{\omega^2 p}{\pi^2} - \frac{u_k^2}{p} \right) I_\omega^{(1)} + \frac{8\omega u_k}{\pi} I_\omega^{(2)}, \quad (7)$$

$$I_\omega^{(1)}(p, u_k) = \int_0^1 (1-t) \operatorname{arctanh} \left[\frac{\cos(\pi u_k t)}{\cosh(\omega p t)} \right] dt, \quad (8)$$

$$I_\omega^{(2)}(p, u_k) = \int_0^1 (1-t) \operatorname{arctan} \left[\frac{\sin(\pi u_k t)}{\sinh(\omega p t)} \right] dt. \quad (9)$$

Minimization of w with respect to p and u yields the equilibrium geometrical parameters, D and a , for the stripe domains as functions of the four control parameters h/l , δ/l , ν , and N in the model. The phase diagram in variables $(h/l, \delta/l)$ for $\nu = 0.1$ and $N = 2$ plotted in Fig. 1 demonstrates the main features of these solutions. Depending on the values of the materials parameters one of the four ground states is realized in the system: the ferro (b) or antiferro (d) stripes, the shifted ferro stripe phase (a), or the antiferromagnetic single domain state (c).

The analytical results presented in Figs. 1 and 2 exemplify a fundamental difference between multidomain states in antiferromagnetically coupled superlattices ($\delta > 0$) and those in multilayers with a ferromagnetic interlayer exchange ($\delta < 0$) or in decoupled nanolayers ($\delta = 0$). In the latter cases the ferro stripe phase is the ground state for arbitrary values of the control parameters δ, h, ν, N [6]. In the antiferromagnetic case the ferro stripes can exist as stable or metastable state (i) only in a certain range of the control parameters (in Fig. 1 below stability line $\alpha - \beta$), and (ii) the ferro stripes are unstable with respect to lateral shifts of domain walls in the adjacent layers.

At the critical line $\alpha - t - \gamma$ this phase transforms into the homogeneous (with $h < h_t = 2.0816l$ for $N = 2$) or antiferro stripe phase ($h > h_t$) by a first-order transition. The ferro stripe mode is the ground state of the system between the transition lines $\alpha - t - \gamma$ and $\delta = 0$.

In the case $N = 2$, the antiferro stripe phase transforms into the homogeneous phase by the unlimited expansion of the stripe period at the critical line $h \equiv h_t$ down to the critical point at $\delta_t = 0.6385l$. Below the transition line $t - \gamma$ the antiferro stripes (with zero shift) still exist as metastable states down to the line $\delta \equiv 0$.

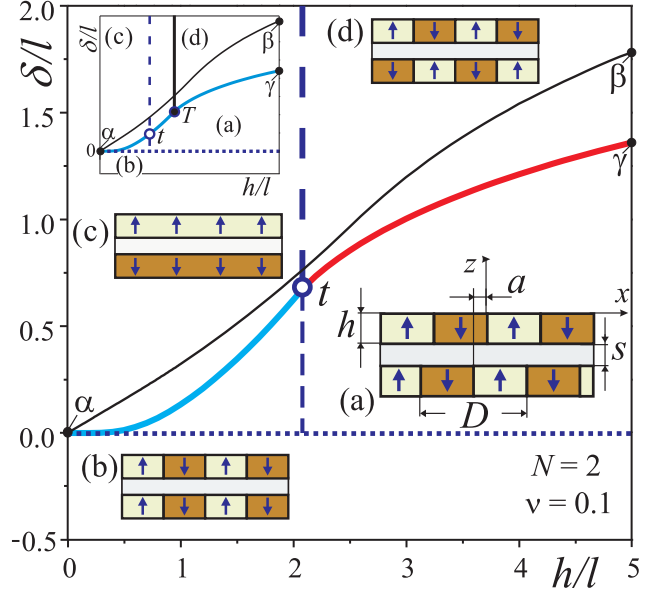


FIG. 1: (Color online) The magnetic phase diagram of states in reduced variables for layer thickness h/l and interlayer exchange δ/l for $N = 2$ and $\nu = s/h = 0.1$. Thick lines indicate the first-order transitions from the *shifted* ferro stripe phase (a) into the antiferro stripe (b) ($t - \gamma$) and homogeneous (c) phases ($\alpha - t$). These critical lines meet in a special critical point t ($h_t = 2.0816l$, $\delta_t = 0.6385l$), where a continuous transition line ends on a first-order line (hollow circle). The thin solid line $\alpha - \beta$ indicates the stability limit of the shifted ferro stripe phase. The dotted line ($\delta = 0$) indicates the second-order transition from the shifted stripes ($a > 0$) in antiferromagnetically coupled systems ($\delta > 0$) into the ferro stripes (b) with $a = 0$ in ferromagnetically coupled or decoupled multilayers ($\delta \leq 0$). At the dashed line $h \equiv h_t$ the antiferro phase (d) continuously transforms into the homogeneous antiferromagnetic states (c) for $\delta > \delta_t$. The dashed line for $\delta < \delta_t$ is the stability limit of the metastable antiferro stripe phase. Inset: sketch of the generic phase diagram for $N \geq 4$ with the discontinuous transition of antiferro stripes into the homogeneous state. Point T is a triple point.

In antiferromagnetic systems with $N \geq 4$, the transition between the antiferromagnetic monodomain and the antiferro stripe phase becomes discontinuous [6]. The general topology of these phase diagrams (inset Fig. 1) display triple points T , where all three ground states co-exist, and the antiferro stripe phase is only metastable at the special critical point t . The “exchange shift” appreciably influences the appearance of the ferro stripe phase. As shown in Fig. 2, the shift a can attain sizeable values. Note that in antiferromagnetically coupled superlattices the exchange energy of the shifted ferro stripes includes a negative contribution linear with respect to a (1). This is the mathematical reason for the instability of the solutions with zero shift. To elucidate this phenomenon we consider small shift distortions in an isolated domain wall. The perturbation energy (per domain wall length)

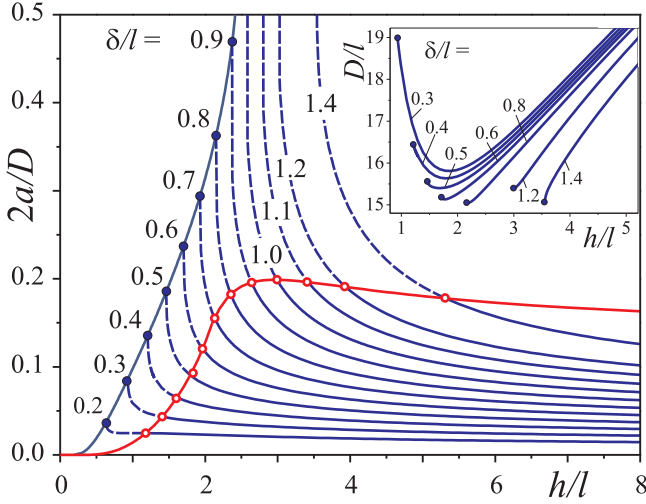


FIG. 2: (Color online) The equilibrium values of the reduced shift $2a/D$ and reduced period (inset) as functions of the reduced thickness h/l for different values of $\delta = J/(2\pi M^2)$ in a two-layer ($N = 2$) with $\nu = 0.1$. Hollow points indicate the solutions at the transition line $\alpha - t - \gamma$, and solid points show the shift at the lability line $\alpha - \beta$.

$\Delta E(a) = \pm 2\pi M^2 e(a)$ can be written as a series with respect to the small parameter $a \ll s$ (the upper (lower) sign corresponds to (anti)ferro stripe states)

$$e(a) = -4\delta a + A(\nu)a^2 - B(\nu)s^{-2}a^4, \quad (10)$$

where $A(\nu) = (2/\pi) \ln[(\nu+1)^2/(\nu(\nu+2))]$, $B(\nu) = (2 + 6\nu + 3\nu^2)/[3\pi(\nu+1)^2(\nu+2)^2]$. The interlayer exchange coupling energy in Eq. (10) is linear with respect to the shift a and *negative* in the case of the ferro stripes. This energy contribution yields solutions with finite $a = 2\delta A^{-1}(\nu)$ for arbitrary strengths of the antiferromagnetic exchange. On the contrary, for the antiferro stripes this energy is *positive* and the solution with *zero* shift remains stable. The analysis shows that for $h > h_t$ the antiferromagnetic stripes exist as metastable state between the transition lines $t - \gamma$ and $\delta = 0$.

In Ref. [3], experimental domain observations are reported on antiferromagnetic [CoPt]/Ru multilayers with $N = 2$ to 10, the magnetization $M = 700$ emu, interlayer exchange $J = 0.45$ erg/cm², and the parameter ν in the a range from 0.072 to 0.6. For these systems, the values of the shift a vary from $a = 4.5$ nm ($\nu = 0.72$) to $a = 18.5$ nm ($\nu = 0.6$). These shifts amount to noticeable parts of the domain size, $D/2 \simeq 130$ nm [3]. The mathematical connection between values of the shift a and the exchange constant J can be used for an experimental determination of the strength of the antiferromagnetic coupling.

The stray-field distributions above the superlattice surfaces are highly sensitive to the appearance of sizeable shifts a . Such effects can be investigated by magnetic force microscopy. Following [10] one can derive an analytical solution for the stray fields $\mathbf{H}^{(m)}$ above an anti-

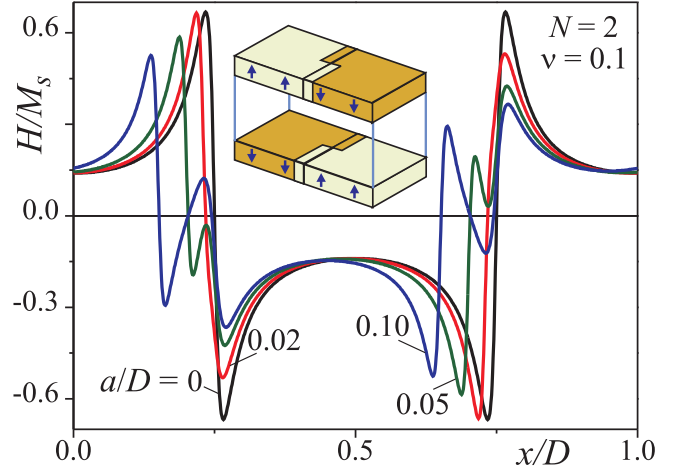


FIG. 3: (Color online) The calculated stray-field profiles $H_z^{(m)}(x/D)$ for shifted ferro stripe modes for a multilayer with $N = 2$ and $\nu = 0.1$. Inset: an isolated antiferromagnetic domain wall with “tiger-tail” distortion, the pattern is periodically repeated along the wall. Such patterns act as nucleation lines for ferro stripe modes.

ferromagnetic two-layer in the shifted ferro stripe states. E.g., the longitudinal component $H_z^{(m)}$ is

$$H_z^{(m)} = 4M[\Upsilon(x, z) + \Upsilon(x + a, z + h + s) - \Upsilon(x, z + h) - \Upsilon(x + a, z + 2h + s)], \quad (11)$$

where $\Upsilon(x, z) = \arctan[\cos(2\pi x/D)/\sinh(2\pi z/D)]$. Peculiarities of the stray-field profiles $H_z^{(m)}(x/D)$ imposed by the exchange shift, as seen in Fig. 3, should be measurable by magnetic force microscopy imaging.

For $h < h_t$ metastable isolated domain walls can exist within the antiferromagnetically coupled ground state (Fig. 1(c)). Usually antiferromagnetic domain patterns are formed during demagnetization cycles in multilayers with the single domain antiferromagnetic ground state (phase (c) in Fig. 1), see, e.g., Refs. [2, 3, 5, 7]. These isolated walls correspond to the solutions with zero shift and preserve their (local) stability down to vanishing antiferromagnetic coupling $\delta = 0$. The results of this paper elucidate the nature of so-called “tiger-tail” patterns visible along these isolated domain walls of the antiferromagnetic phase [5, 7] and recently observed as a “mixed state” of antiferro and ferro stripes [7]. Isolated domain walls within the homogeneous antiferromagnetic phase can play the role of nucleation centers for the ferro stripe phase. Within the metastability region of the shifted ferro stripe phase (area between $\alpha - \beta$ and $\alpha - \gamma$ lines in Fig. 1) sinusoidal distortions of antiferromagnetic domain walls transform into spin configurations corresponding to the ferro stripe phase (Inset in Fig. 3). Such patterns have been reported in Ref. [7] and were called “tiger-tails”. During the first-order phase transition at the $\alpha - \gamma$ line of the phase diagram, where the monodomain an-

tiferromagnetic phase and the shifted ferro stripes coexist, “tiger-tails” develop into ferro stripe patterns. The transformation of “tiger-tails” into extended areas with the ferro stripe phase was observed in Ref. [7]. This is a “mixed state” composed of the homogeneous antiferromagnetic and the multidomain ferromagnetic phases. This particular evolution at a first-order transition, when magnetic phases nucleate within domain walls of competing phases have previously been observed in various bulk magnetic systems [11].

In conclusion, we have demonstrated that, in antiferromagnetically coupled multilayers, ferromagnetic stripes are unstable with respect to a lateral shift. These multidomain configurations form *shifted ferro stripe* states (Fig. 1 (a)). On the contrary, the inhomogeneous magnetic states with antiparallel arrangement in adjacent layers (antiferro stripes (d) and isolated antiferromagnetic domain walls) have stable configurations with zero shift [12].

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* Corresponding author ; Electronic address:
m.kyselov@ifw-dresden.de

[†] Electronic address: u.roessler@ifw-dresden.de

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